IC provides optimal lead-acid-battery charging cycles

A battery-charger IC can help reduce the cost and effort of implementing optimal charge and hold cycles for lead-acid batteries. By understanding the IC's basic charging principles, as well as the chip's auxiliary features, you can devise charging circuits that let you get the most out of a lead-acid battery.

Rich Valley, *Unitrode Corp*

A dedicated battery-charger IC, the UC3906, lends itself to a variety of lead-acid battery-charging schemes. The circuit ensures that a battery receives the proper charge and hold cycles. Such a control function has three requirements: precision sensing and control of both voltage and current, logic to control the IC's charging cycle, and temperature compensation to allow proper charging at temperature extremes.

Discrete solutions to the charging problem require many components and a significant design effort. Using the UC3906, however, you need choose just a few external-component values. The IC has all the control and sensing functions necessary to optimize cell capacity and life in a range of battery applications.

A brief survey of the UC3906's internal circuitry (Fig 1) and operating principles will help you to understand the applications examples that follow and to use the IC in other applications. By controlling the onboard driver, separate voltage-loop and current-limit amplifiers regulate the charger's output-voltage and -current levels. The driver transistor can supply 25 mA of base drive to an external pass element. Voltage- and current-sense comparators monitor the battery's condition and respond with logic inputs to the charge-state logic.

Remotely disable the charger

You can use the IC's charge-enable comparator to remotely disable the charger. The comparator's 25-mA trickle-bias output is active high when the driver is disabled. You can combine all the mentioned attributes of the UC3906 to implement a low-current turn-on mode in a charger, and thereby prevent high-current charging in the presence of abnormal conditions (for example, a shorted or reversed battery).

A salient feature of the UC3906 is its precision reference. The reference voltage has temperature compensation specifically conceived to track the temperature characteristics of lead-acid batteries. The IC operates with a 1.7-mA supply current; this low current minimizes on-chip power dissipation and permits accurate temperature sensing.

In addition, the IC includes a supply-undervoltage sensing circuit that initializes charging cycles upon power-up. The circuit also drives a logic output that indicates the presence of input power. The UC3906 is

The charging methods used to maintain or replenish the charge on a lead-acid battery affect cell performance; making an optimum charger is no trivial task.

specified for operation over 0 to 70°C; the UC2906 operates over −40 to +70°C.

Fig 2 gives a state diagram for a sealed lead-acid battery charger (**Fig 3**). The charger, called a dual-level float charger, has three states: a high-current bulk-charge state, an overcharge state, and a float state.

A charge cycle begins with the charger in the bulk-charge state. In this mode, the charger takes on the role of a current source that provides a constant charge current of I_{MAX}. The charger senses the battery voltage; when the voltage reaches the transition threshold (V_{12} in **Fig 2**), the charger begins its overcharge cycle. During the overcharge period, the charger regulates the battery at an elevated voltage (V_{OC}) until the charge rate drops to a specified transition current (I_{OCT}).

When the current tapers to I_{OCT}, with the battery's voltage at the elevated level, the capacity of the cell should be nearly 100%. At this point, the charger turns into a voltage regulator with the precisely defined output voltage V_F. The output voltage of the charger in this third state sets the float level for the battery.

Using the UC3906, you can implement the described charge and hold cycles with few external parts and little design effort. The equations in **Fig 3** provide the means to calculate the element values for specific applications. The external resistors R_S, R_A, R_B, and R_C determine the programming of all the charger's voltage and current levels.

You can best understand the charger in **Fig 3** by

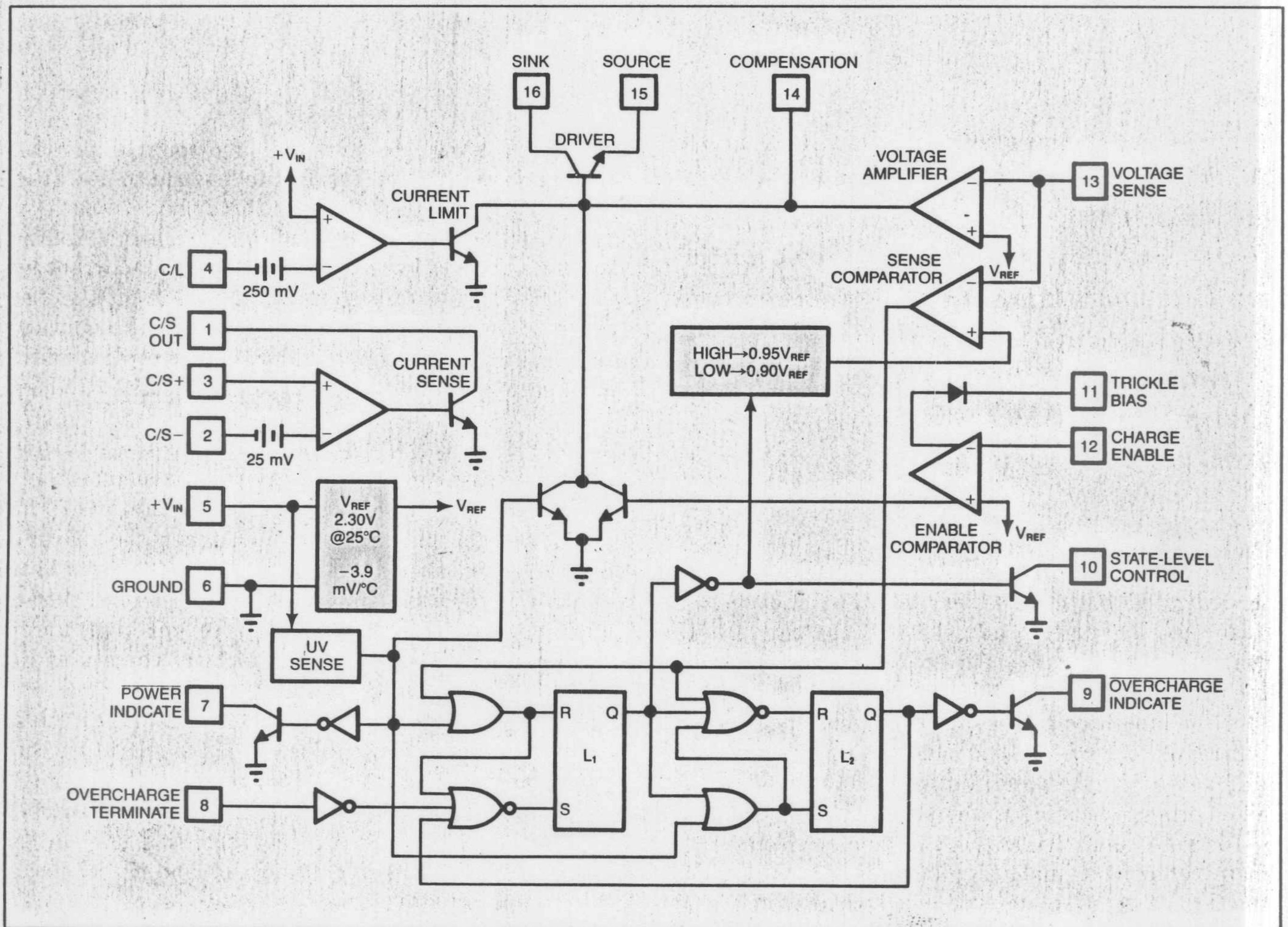


Fig 1—A charger IC for sealed lead-acid batteries, *the UC3906 combines precision voltage and current sensing with voltage- and current-output control to provide optimum battery-charging cycles. Internal charge-state logic sequences the device through its charging cycles. The voltage-control and -sensing functions derive their reference levels from an internal voltage whose temperature coefficient closely matches that of lead-acid cells.*

tracing a charge cycle. Either of two conditions initiates the bulk-charge state at the beginning of the cycle. One condition occurs when you turn on the input supply to the charger; the second condition, a low-voltage condition on the battery, occurs while the charger is in the float state. The undervoltage-sensing circuit in the UC3906 measures the input supply to the IC. When the supply voltage drops below approximately 4.5V, the sensing circuit forces the two state-logic latches **(Fig 1)** into the bulk-charge condition: L_1 reset and L_2 set.

The undervoltage circuit also disables the driver output during undervoltage. To enter the bulk-charge state while power is on, the charger must first be in the float state (both latches set). The signal from the voltage-sense comparator to the charge-state logic re-

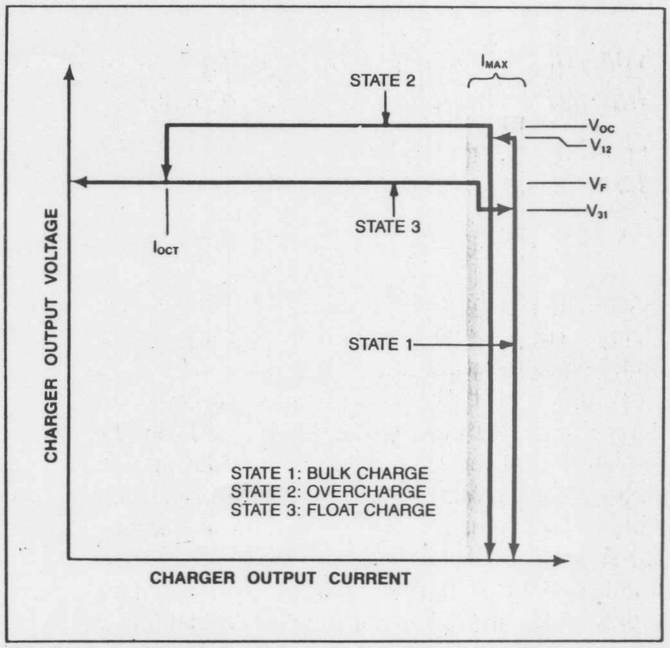


***Fig 2—A dual-level float charger** has three charge states. A constant-current bulk charge returns 70 to 90% of capacity to the battery; the remaining capacity returns during an elevated constant-voltage overcharge. The float-charge state maintains a precise voltage across the battery to optimize standby life.*

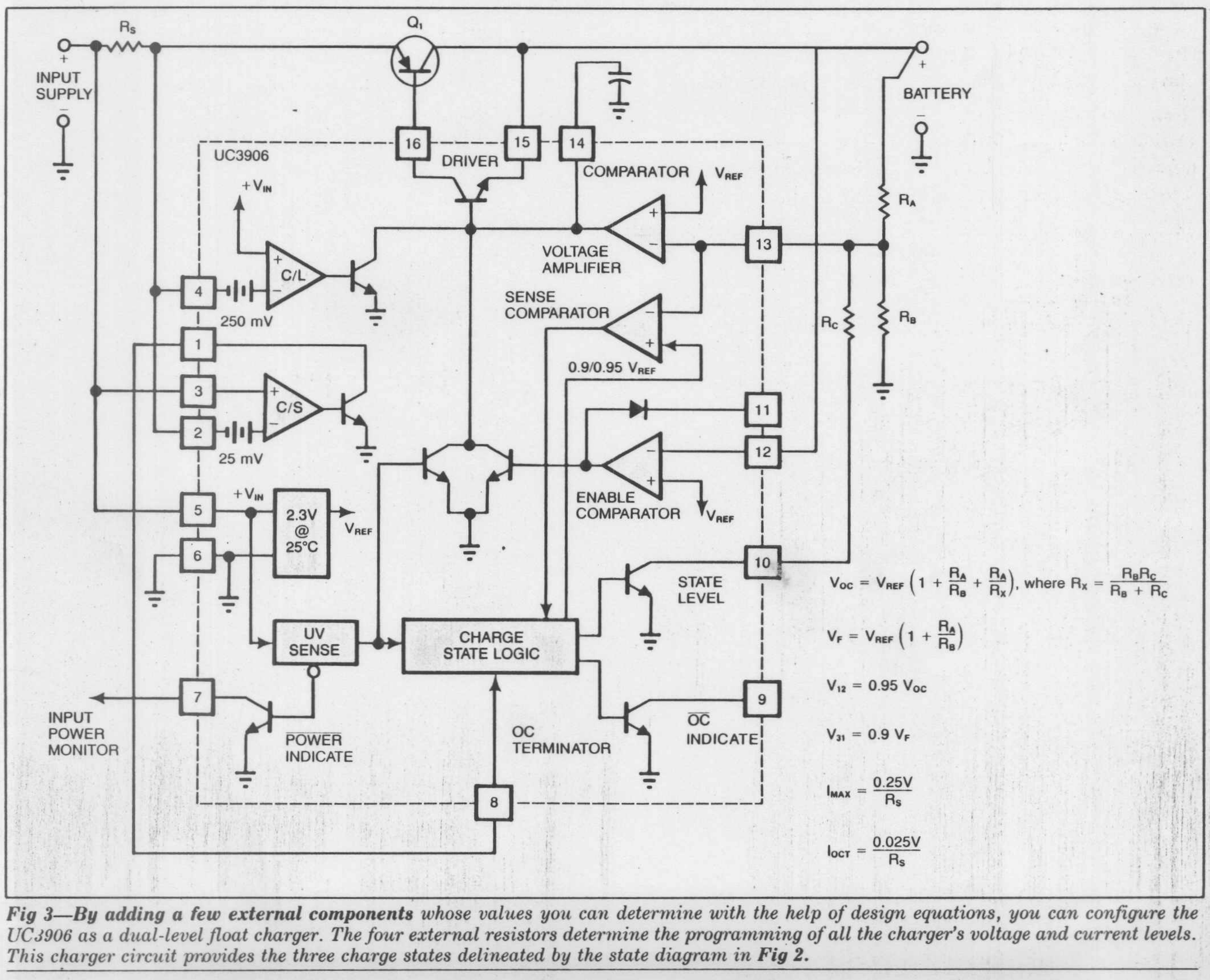


***Fig 3—By adding a few external components** whose values you can determine with the help of design equations, you can configure the UC3906 as a dual-level float charger. The four external resistors determine the programming of all the charger's voltage and current levels. This charger circuit provides the three charge states delineated by the state diagram in **Fig 2**.*

Applying a constant float voltage to a fully charged cell is the best way to prolong the cell's life; however, the temperature coefficient must match that of the battery.

ports on the battery voltage. If the battery voltage drops, this signal resets L_1, thereby initiating the bulk-charge state.

With L_1 reset, the state-level control output is active low. While this pin's voltage is low, R_C shunts divider resistor R_B, thereby raising the regulating level of the voltage loop. When the battery needs a charge, the voltage amplifier is in its saturated state, trying to turn on the driver to increase the battery voltage. In this condition, the current-limit amplifier overrides the voltage amplifier's output. The current-limit amplifier controls the driver, regulating the output current at a constant level.

The voltage at the internal, noninverting input to the voltage-sense comparator equals 0.95 times the internal reference voltage. As the battery becomes charged, its voltage rises; when the scaled battery voltage at pin 13 (the inverting input to the same comparator) reaches $0.95V_{REF}$, the sense comparator's output switches low. By switching low, the comparator resets the second latch and initiates the overcharge state. The overcharge indicator's output then goes low (providing the only externally observable change in the charger).

The initiation of the overcharge state arms the set input of the first latch (assuming no reset signal is present), so that when the overcharge-terminate input goes high, the charger can enter the float state. In the overcharge state, the charger continues to supply the maximum current. As the battery voltage reaches the elevated regulating level, V_{OC}, the voltage amplifier takes command of the driver, regulating the output voltage at a constant level. The voltage at pin 13 now equals the internal reference voltage. The battery is completing its charge cycle, and the charge acceptance starts to taper off.

As configured in **Fig 3**, the current-sense comparator continuously monitors charge rate by sensing the voltage across R_S. The output of the comparator connects to the overcharge-terminate input. Whenever the charge current is less than I_{OCT} (25 mV/R_S), the comparator's open-collector output is off. When the charge current reaches this transition current, as the charge rate tapers off in the overcharge state, the off condition of the comparator's output allows an internal 10-μA pullup current at pin 8 to pull that point high.

You can add a capacitor from pin 8 to ground to

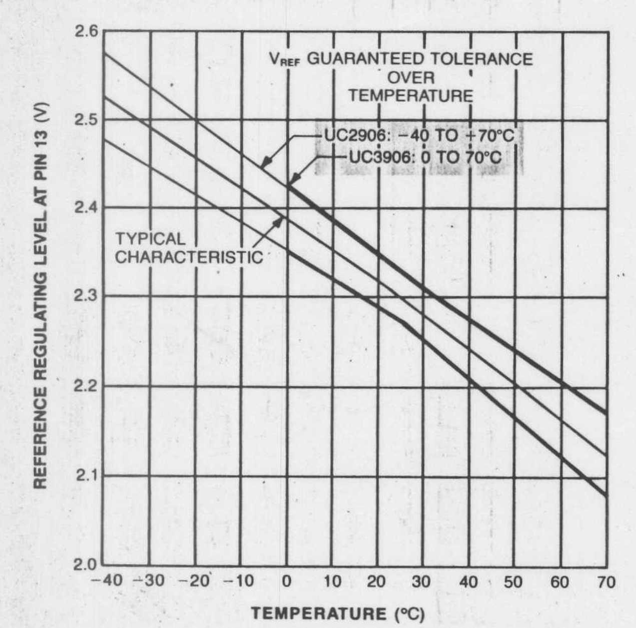


Fig 4—The specially tailored temperature compensation *of the UC3906's reference matches a lead-acid battery's temperature coefficient. The compensation allows the charger to provide the proper charge and hold characteristics at temperature extremes.*

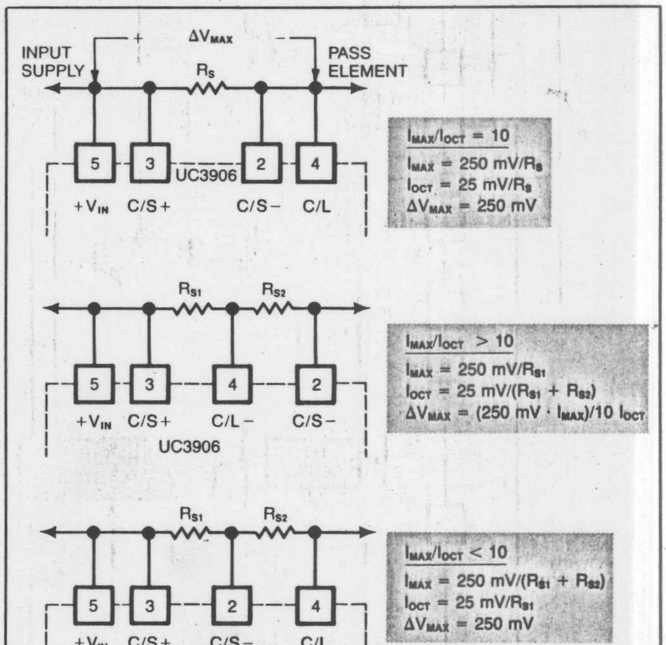


Fig 5—Although the ratio of the bulk-charge current *to the overcharge-terminate current is fixed at 10, you can easily obtain other ratios by changing the values and connections of the external resistors. Ratios greater than 10, however, exact the penalty of increased voltage drop across the sensing network at I_{MAX}.*

provide a delay to the overcharge-terminate function, thereby preventing the charger from prematurely entering the float state if the charging current temporarily drops. When the voltage at pin 8 reaches its 1V threshold, latch L_1 sets, setting L_2 as well, and the charger enters the float state. At this point, the state-level output is off, effectively eliminating R_C from the divider and lowering the regulating level of the voltage loop to V_F (**Fig 2.**)

In the float state, the charger maintains V_F across the battery, supplying currents of 0A to I_{MAX} as required. In addition, the setting of latch L_1 switches the voltage-sense comparator's reference level from 0.95 to 0.9 times the internal reference. If the battery now discharges to a voltage level 10% below the float level, the sense comparator's output resets L_1 and the charge cycle begins again.

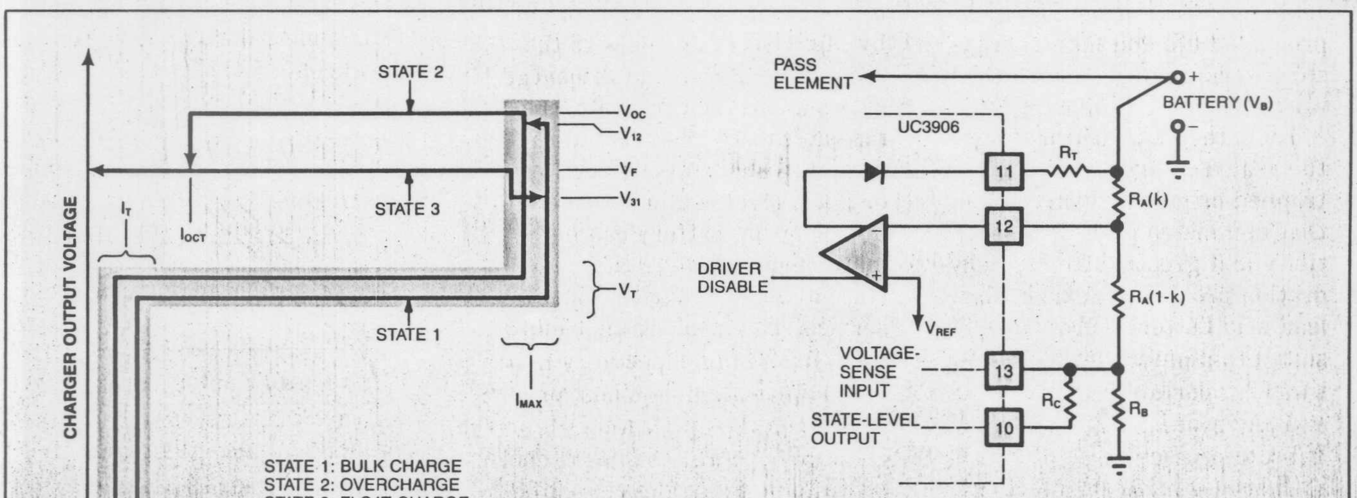
The float voltage V_F, as well as V_{OC} and the transition voltages, are proportional to the UC3906's internal reference. This reference has a temperature coefficient of −3.9 mV/°C. The temperature function is within the compensation range recommended by most battery manufacturers. The importance of the control of the charger's voltage levels is reflected in the tight specification of the UC3906's reference and its change with temperature (**Fig 4**).

You can set the UC3906's I_{MAX}, I_{OCT}, V_{OC}, and V_F values independently. I_{MAX}, the bulk-charge rate, can be as high as the available power source will allow or the series-pass device can handle. Battery manufacturers recommend charge rates in the C/20 to C/3 range, where C is the battery's ampere-hour rating (see **box**, "Battery capacity, life, and optimum charging"). Some suppliers claim that rates as high as 2C and beyond are satisfactory if the charger includes overcharge protection.

You should choose I_{OCT}, the overcharge-terminate threshold, to correspond as closely as possible to the 100%-recharge level. The proper value depends on the overcharge voltage (V_{OC}), and on the cell's charge-current tapering characteristics at V_{OC}. I_{MAX} and I_{OCT} are functions of the offset voltages built into the current-limit amplifier and current-sense comparator, respectively, and of the resistors used to sense current.

The offsets have a fixed ratio of 250:25 mV. If ratios other than 10 are necessary, you must use separate current-sensing resistors or a current-sense network. **Fig 5** gives examples of these alternatives. The penalty for using these external elements is increased voltage drop across the sensing network during high-current (I_{MAX}) charging.

Another method for controlling the overcharge state



$V_T = V_{REF}\left[1 + \frac{kR_A}{(1-k)R_A + R_X}\right]$, WHERE k IS A CONSTANT ≤ 1 AND $R_X = \frac{R_B R_C}{R_B + R_C}$.

$I_T = \frac{V_{IN} - V_T - 2V}{R_T}$, WHERE V_{IN} IS THE INPUT SUPPLY AND 2V IS THE DROP FROM V_{IN} TO PIN 11.

*Fig 6—**The charge-enable comparator,** with its trickle-bias output, protects the charger. The current foldback at low battery voltages prevents high-current charging of batteries with shorted cells (or improperly connected batteries) and also protects the pass element from excessive power dissipation.*

Simple charge schemes cannot optimize a cell's capacity/life tradeoff; charge cycles must adapt to a battery's type, state of charge, and temperature coefficient.

is to use the overcharge-indicate output, pin 9, to initiate an external timer. At the onset of the overcharge cycle, the overcharge-indicate output goes low. A timer triggered by pin 9's signal could then activate the overcharge-terminate input, pin 8, after the occurrence of a timed overcharge.

In **Fig 3**'s circuit, the float (V_F) and overcharge (V_{OC}) voltages are functions of the internal reference and the external resistor network comprising R_A, R_B, and R_C. For the dual-level float charger, the ranges at 25°C for V_F and V_{OC} are typically 2.3 to 2.4V and 2.4 to 2.7V, respectively. Battery manufacturers usually specify the float-charge level tightly.

The overcharge level, V_{OC}, is not as critical as the float level, and it varies as a function of the charge rate used. The absolute values of the divider resistors can be high—a divider current of 50 μA exacts an accuracy penalty (arising from input bias-current offsets) of less than 0.5%.

IC lets you add functions to charger

In addition to simply charging batteries, you can use the UC3906 to add auxiliary functions to the charger, functions that would otherwise entail discrete-component additions. For example, you can use the enable comparator and its trickle-bias output in several different ways. Modification of the state diagram in **Fig 2** to establish a low-current turn-on charger mode **(Fig 6)** is one simple task. By reducing the output current of the charger when the battery voltage is below a program-

Battery capacity, life, and optimum charging

Battery technology has come a long way in recent years, and batteries now provide portability and fail-safe protection for a new generation of electronic systems. Although several battery technologies have evolved, the lead-acid cell—with its combination of prolonged life and high energy-storage capacity—remains the workhorse of the industry.

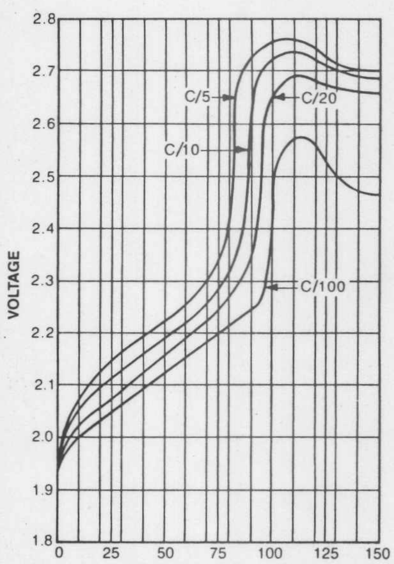
The latest lead-acid battery, the sealed-cell type, uses a trapped or gelled electrolyte that eliminates positional sensitivity and greatly reduces dehydration problems. Sealed-cell lead-acid batteries are well suited to uninterruptible power supplies, portable equipment, and any system that requires fail-safe protection.

Charging methods affect the capacity and life of a lead-acid battery. Capacity, C, refers to the number of ampere-hours a charged battery is rated to supply at a given discharge rate. Rated capacity generally serves as the unit for expressing charge- and discharge-current rates. For example, a 2.5-Ahr battery charging at 500 mA is charging at a C/5 rate.

Two measures of battery life

Battery life is measured in one of two ways: cycle life or standby life. Cycle life refers to the number of charge and discharge cycles a battery can endure before its capacity is reduced to some threshold level. Standby, or float, level is a measure of how long the battery can be maintained in a fully charged state and still provide proper service. The measure that indicates useful life expectancy in a given application depends, of course, on the application.

Simple charge schemes cannot begin to optimize the tradeoffs between battery capacity and life. To provide reasonable recharge times with 100% return of capacity, a charge cycle must adapt to the state of the charge and the temperature of the battery. To return the bulk of the expended capacity in sealed (or recombinate) cells following a high-current charge, a controlled



NOTE:
CELLS CHARGED AT CONSTANT CURRENT AT 25°C.
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***Fig A—Depending on charge rate,** overcharge reactions (indicated by the sharp rise in battery voltage) begin at a point well below 100% return of capacity.*

mable threshold, the charging system provides protection against the following:

- High-current charging of a string with a shorted cell, resulting in excessive outgassing from the remaining cells in the string
- Dumping charge into a battery that's connected backwards
- Excessive power dissipation in the charger's pass element.

As shown in **Fig 6**, the enable comparator's input taps off the battery-sensing divider. When the battery voltage is below the resulting threshold, V_T, the driver in the UC3906 becomes disabled and the trickle-bias output goes high. You can then use resistor R_T, connected from the trickle-bias output to the battery, to set a trickle current (≤25 mA) to the battery. This action helps the charger discriminate between severely discharged cells and damaged or improperly connected cells.

In applications for which the charger is always connected to the battery and load currents are small, you might have to minimize the battery load presented by the charger when the input power is removed. You can take two precautions that prevent the flow of reverse current into the charging circuit. In **Fig 7**, the diode in series with the pass element prevents any reverse current from flowing in this path.

To maintain accurate voltage control, make sure the sense divider still derives its reference from the battery. Connecting the divider to the open-collector pow-

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overcharge should take place. For unsealed cells, you must minimize the overcharge reaction. After the overcharge, or at the onset of the overcharge, the charger should switch to a precise float condition.

During the charge cycle of a typical lead-acid cell, lead sulfate ($PbSO_4$) is converted to lead on the cell's negative plate and to lead dioxide on the positive plate. When the majority of the lead sulfate has been converted, overcharge reactions begin. The typical result of overcharge is the generation of hydrogen and oxygen gas.

Overcharge yields water loss

In unsealed batteries, overcharge results in the immediate loss of water. In sealed cells, at moderate charge rates, the majority of the hydrogen and oxygen recombine before dehydration occurs. In either type of cell, prolonged charging rates significantly higher than C/500 result in dehydration, accelerated grid corrosion, and reduced service life.

The onset of the overcharge reaction depends on charge rate. At charge rates greater than C/5, less than 80% of the cell's previously discharged capacity will be returned as the overcharge reaction begins. For overcharge to coincide with 100% return of capacity, charge rates must typically be lower than C/100.

Voltage rise affects overcharge

Also, to accept higher rates, the battery voltage must be allowed to increase as overcharge is approached. The curves in **Fig A** show cell voltage vs percent return of previously discharged capacity for a variety of charge rates. The overcharge reaction begins at the point where the cell voltage rises sharply, and becomes excessive as the curves level out and start down again.

Once a battery is fully charged, the best way to maintain the charge is to apply a constant voltage to the battery. The charge circuit thus must supply the correct float-charge level—high enough to compensate for self-discharge, but not so high that the battery degrades from overcharging. With the proper float charge, you can expect sealed lead-acid batteries to give standby service for six to 10 years. An error of just 5% in a float charge, however, can halve this life.

To compound the preceding concerns, the voltage characteristics of a lead-acid cell have a pronounced negative temperature dependence: approximately −4 mV/°C per 2V cell. In other words, a charger that works perfectly at 25°C might not maintain a full charge at 0°C and, conversely, might drastically overcharge a battery at 50°C. To function properly at temperature extremes, a charger requires compensation to track the battery's temperature coefficient.

A dual-level float charger provides three charge states and maintains a lead-acid battery's capacity at nearly 100%.

er-indicate output, pin 7, eliminates the discharge path the divider would present if connected to ground. Connected in this manner, the divider string is in series with an essentially open circuit when input power is removed. When power is present, the open-collector device is on and thus holds the end of the divider string to near-ground potential. The saturation voltage of the open-collector transistor is specified at <50 mV with 50-μA load current.

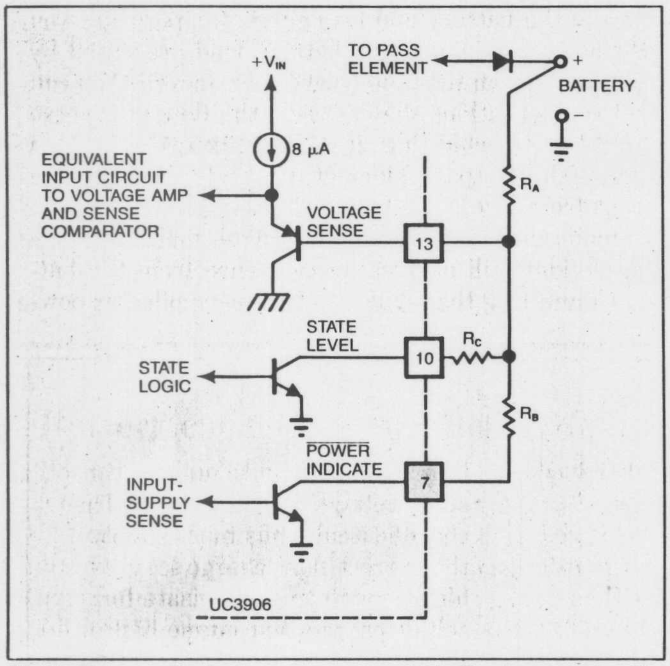

Fig 7—You can eliminate reverse current into the charger (when the charger is tied to the battery and no input power exists) by using a diode in series with the pass element and returning the divider string to the power-indicate pin (pin 7).

Protect against overdischarge

Overdischarging a lead-acid cell, like overcharging, can severely shorten the cell's life. **Fig 8** illustrates the use of the enable comparator and its output to build overdischarge protection into a charger. The circuit monitors the discharging of the battery and disconnects all loads from the battery when the voltage reaches a specified cutoff point. The load remains disconnected from the battery until input power returns and the battery is recharged.

The scheme uses a relay, controlled by Q_1, between the battery and its load. When primary power is available, the bias path through D_5 holds Q_1 on. The battery is charging (or charged), and the trickle-bias output at pin 11 is off. When you remove the input power, C_2 provides holdup time at the load as Q_1 turns off, thereby closing the relay as current flows through R_1 and R_2. The battery is now providing power to the load and, through D_1, to the charger.

The charger's current consumption is typically less than 2 mA. As the battery discharges, the UC3906 continues to monitor its voltage. When the voltage reaches the cutoff level, set by the R_5-to-R_8 divider

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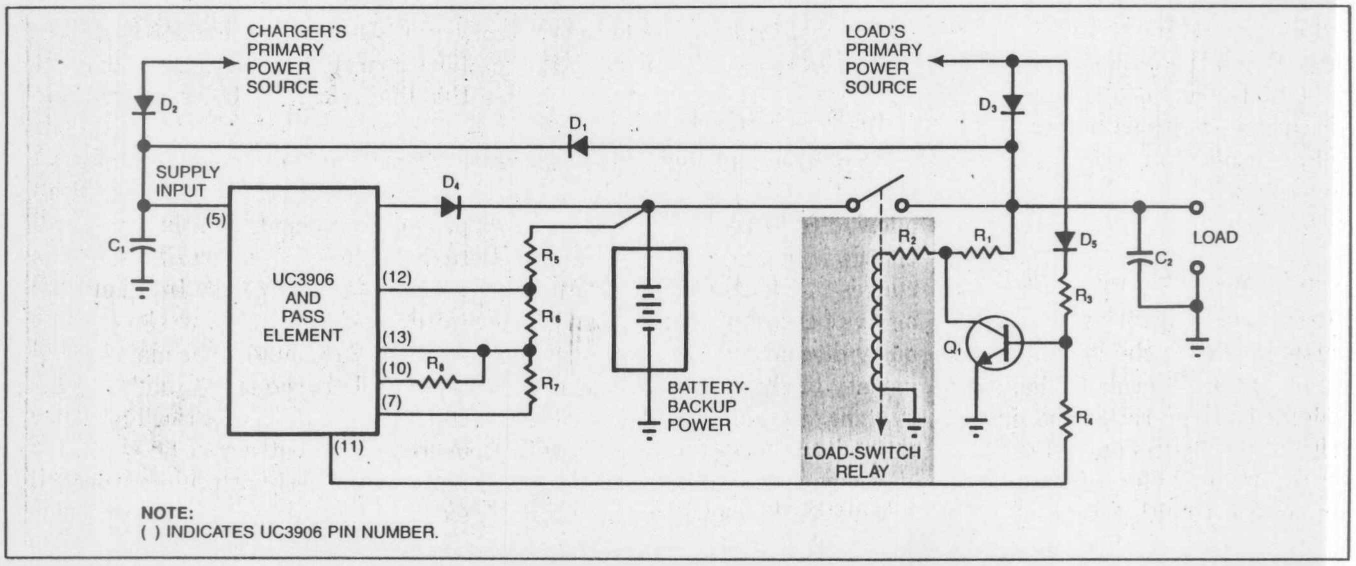


Fig 8—Using the enable comparator *to monitor battery voltage, you can set a precise discharge cutoff voltage. When the battery voltage reaches the cutoff threshold, the trickle-bias output switches off the load-switch relay and the battery's circuit remains open until input power returns.*

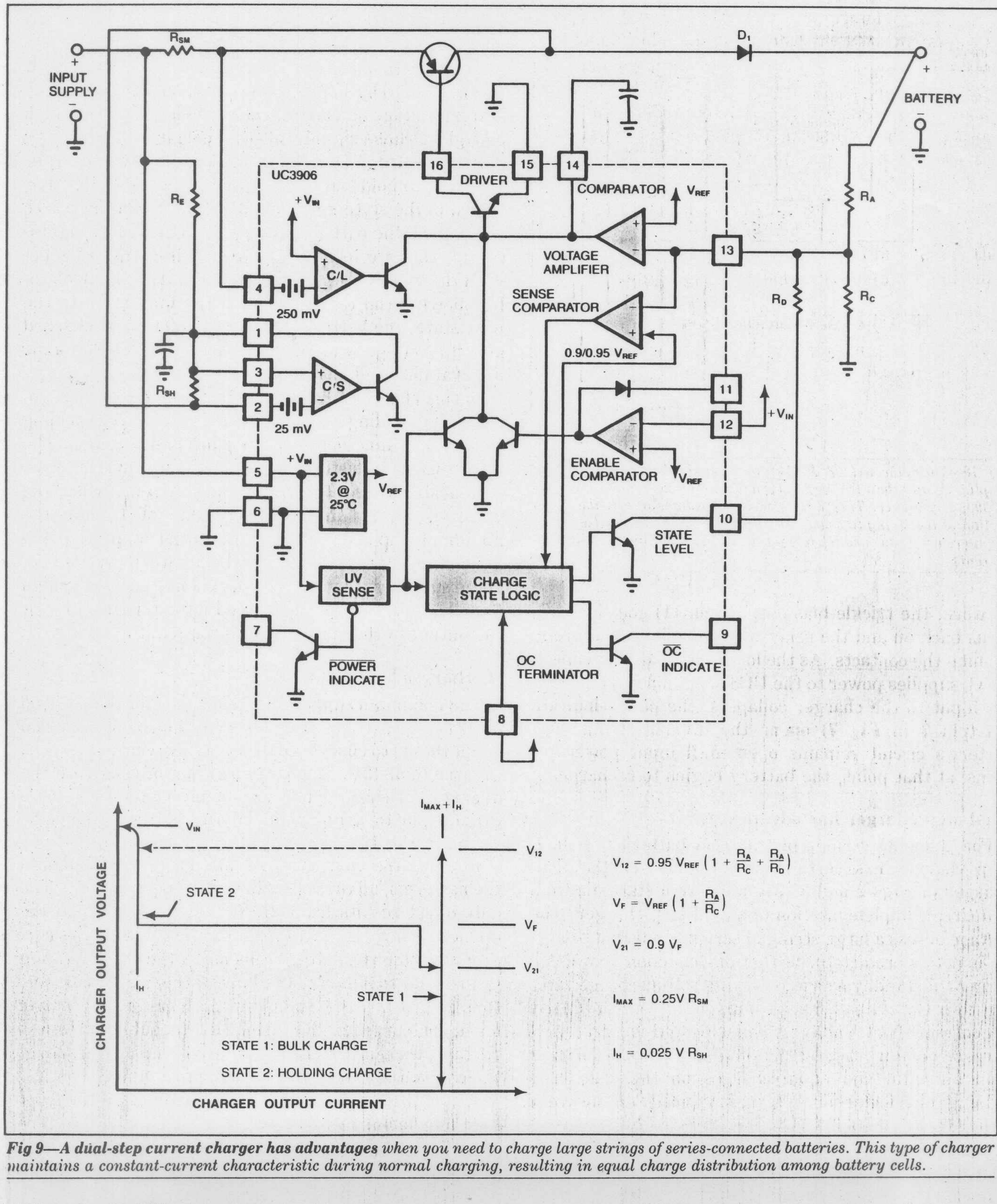


Fig 9—A dual-step current charger has advantages *when you need to charge large strings of series-connected batteries. This type of charger maintains a constant-current characteristic during normal charging, resulting in equal charge distribution among battery cells.*

You can use the auxiliary functions of the battery-charger IC to provide safety features for batteries and to protect externally connected series-pass elements.

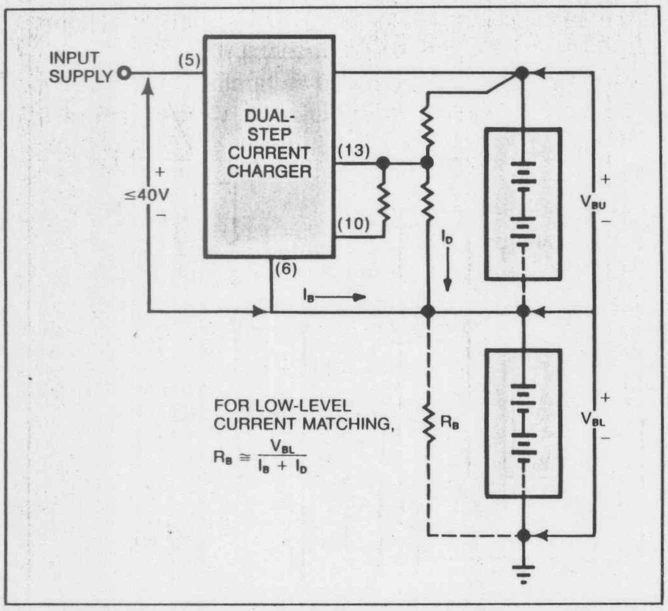


Fig 10—You can use a dual-step current charger with input supplies greater than 40V if you use a tap on the battery string for the UC3906's reference. The charger uses the voltage across the upper portion of the string to sense transition points. To minimize charging-current offsets, use R_B to cancel the UC3906's bias and divider currents.

network, the trickle-bias output (pin 11) goes high. Q_1 turns back on and the relay current collapses, thereby opening the contacts. As the load voltage drops, capacitor C_1 supplies power to the UC3906 to hold Q_1 on. Once the input to the charger collapses, the power-indicate pin (pin 7 in **Fig 7**) opens the divider string. The battery's circuit remains open until input power returns; at that point, the battery begins to recharge.

Dual-step charger has advantages

For charging strings of lead-acid batteries, a dual-step charger has certain advantages over the float charger of **Figs 2** and **3. Fig 9** shows a state diagram and circuit implementation of a dual-step charger. The voltage across a large string of series-connected batteries is not as predictable as that of a common 3- or 6-cell string. In standby service, varying self-discharge rates can alter the state of charge of individual cells if you use a constant float voltage. The elevated-voltage, low-current holding state of the dual-step current charger maintains full and equal charges on the cells. The holding (or trickle) current, I_H, is typically on the order of 0.0005C to 0.005C.

To provide adequate and accurate recharge, this charger uses a bulk-charge state with temperature-compensated transition thresholds V_{12} and V_{21}. Instead of initiating an elevated-voltage overcharge, the charger switches to a constant-current holding state when it reaches V_{12}. The holding current should maintain the battery voltage at a slightly elevated level, but not high enough to cause significant overcharging.

If the battery current increases, then the charger attempts to hold the battery voltage at the V_F level as shown in the state diagram. Battery-current increases can occur if the battery's temperature increases significantly, thereby increasing the self-discharge rate beyond the value of the holding current. Also, immediately following the transition from the bulk state to the float state, the battery will be only 80 to 90% charged and its voltage will drop to the V_F level for some interval until full charge is achieved.

In this charger, the current-sense comparator regulates the holding current. The level of the holding current is a function of the sensing resistor, R_{SH}. The other series resistor, R_E, allows the current-sense comparator to regulate the holding current. Select the value of R_H by dividing the value of I_H into the minimum input-to-output differential expected between the battery voltage and the input-supply voltage. If the supply is very large or the holding current is high (>25 mA), then you might need an external buffer at the output of the current-sense comparator.

IC charges battery strings

The maximum supply voltage allowed for the UC3906 is 40V. With some modifications, however, you can adapt the IC to charge a battery string whose voltage is greater than 40V. To charge a string of cells with the dual-step current charger, connect the UC3906's ground pin to a tap point on the battery string, as shown in **Fig 10.**

Because the charger is regulating the current into the batteries, all the cells will receive equal charge. The only offset results from the IC's bias current and the divider-string current; these currents add to the current charging the battery cells below the tap point. You can add R_B to subtract the bulk of this added current, thus improving the ability of the charger to control low-level currents. By using R_B to subtract excess current, the voltage trip points are based on the sum of the cell voltages on the high side of the tap.

When choosing an external pass device, you must take four factors into account:

- The pass device must have sufficient current- and power-handling capability to accommodate the

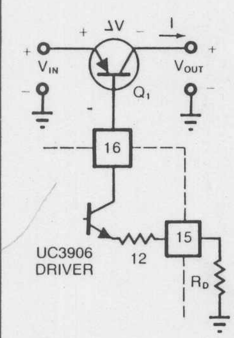
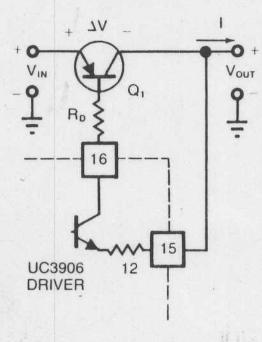
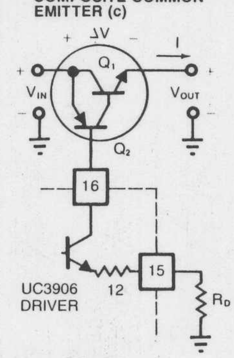
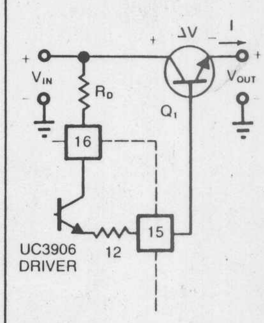
desired maximum charging rate at the maximum input/output differential.

- The device must have a high enough current gain at the maximum charge rate to keep the required drive current to less than 25 mA.
- The type of device used (pnp, npn, or FET), and its configuration, may be dictated by the minimum input-to-output differential at which the charger must operate.
- The open-loop gains of both the voltage- and current-control loops are dependent on the pass element and its configuration.

Fig 11 shows four driver configurations, along with some rough guidelines on applicable current ranges as well as the resulting minimum input-to-output differentials. **Fig 11** also contains equations for the power dissipation that results in the UC3906 die, equations for a resistor (R_D) you can add to minimize this dissipation, and expressions for the open-loop gains of both the voltage and current loops.

Compensating the loop

As reflected in the gain expressions in **Fig 11,** the open-loop voltage gains of both the voltage- and cur-

	COMMON-EMITTER PNP (a)	COMPOSITE FOLLOWER (b)	COMPOSITE COMMON EMITTER (c)	NPN EMITTER FOLLOWER (d)
TOPOLOGY				
CURRENT RANGE	25 mA<I<1000 mA	25 mA<I<1000 mA	600 mA<I<15A	25 mA<I<1000 mA
MINIMUM INPUT/OUTPUT DIFFERENTIAL	$\Delta V > 0.5V$	$\Delta V > 2V$	$\Delta V > 1.2V$	$\Delta V > 2.7V$
UC3906 DRIVER DISSIPATION	$P_D = \left(\frac{V_{IN} - 0.7}{\beta_{Q1}}\right) I - \frac{I^2 R_D}{\beta_{Q1}^2}$	$P_D = \left(\frac{V_{IN} - 0.7 - V_{OUT}}{\beta_{Q1}}\right) I - \frac{I^2 R_D}{\beta_{Q1}^2}$	$P_D = \left(\frac{V_{IN} - 0.7}{\beta_{Q1}\beta_{Q2}}\right) I - \frac{I^2 R_D}{\beta_{Q1}^2 \beta_{Q2}^2}$	$P_D = \frac{V_{IN} - V_{OUT} - 0.7}{\beta_{Q1}} - \frac{I^2 R_D}{\beta_{Q1}^2}$
DISSIPATION-REDUCTION RESISTOR R_D	$R_D = \frac{V_{IN(MIN)} - 2}{I_{MAX}} (\beta_{Q1(MIN)})$	$R_D = \frac{V_{IN(MIN)} - V_{OUT(MAX)} - 1.2}{I_{MAX}} (\beta_{Q1(MIN)})$	$R_D = \frac{V_{IN(MIN)} - 0.7}{I_{MAX}} (\beta_{Q1(MIN)}\beta_{Q2(MIN)})$	$R_D = \frac{V_{IN(MIN)} - V_{OUT(MAX)} - 1.2}{I_{MAX}} (\beta_{Q1(MIN)})$
OPEN-LOOP GAIN VOLTAGE LOOP	$A_{OV} = \frac{Z_C}{1300}\left(\frac{\beta_{Q1} Z_O V_{REF}}{(R_D + 12)\, V_{OUT}}\right)$	$A_{OV} = \frac{Z_C}{1300}\left(\frac{V_{REF}}{V_{OUT}}\right)$	$A_{OV} = \frac{Z_C}{1300}\left(\frac{\beta_{Q1}\beta_{Q2} Z_O V_{REF}}{(R_D + 12)\, V_{OUT}}\right)$	$A_{OV} = \frac{Z_C}{1300}\left(\frac{V_{REF}}{V_{OUT}}\right)$
OPEN-LOOP GAIN CURRENT LOOP	$A_{OC} = \frac{Z_C}{300}\left(\frac{\beta_{Q1} R_S}{R_D + 12}\right)$	$A_{OC} = \frac{Z_C}{300}\left(\frac{\beta_{Q1} R_S}{\beta_{Q1} Z_O + 12}\right)$	$A_{OC} = \frac{Z_C}{300}\left(\frac{\beta_{Q1}\beta_{Q2} R_S}{R_D + 12}\right)$	$A_{OC} = \frac{Z_C}{300}\left(\frac{\beta_{Q1} R_S}{\beta_{Q1} Z_O + 12}\right)$

NOTES:
Z_C IS IMPEDANCE AT COMPENSATION PIN 14.
Z_O IS IMPEDANCE AT CHARGER OUTPUT.

Fig 11—Many driver/pass-element configurations *are possible, and the tradeoffs are between current gain, input/output differential, and in some cases, power dissipation in the UC3906. If dissipation poses a problem, you can reduce it by adding a resistor in series with the UC3906's driver.*

Because the input offset voltages of the current amplifier and sense comparators have little temperature dependence, dissipation has no effect on current levels.

rent-control loops are dependent on the impedance Z_C at the compensation pin. By adjusting the value of this impedance, you can provide closed-loop stabilization to both loops. Using the expressions given, you can perform a detailed analysis of the loops to predict gain and phase margins. In doing so, don't forget to account for all the poles in the open-loop transfer functions.

In the common-emitter driver examples in **Fig 11a** and **Fig 11c**, the equivalent load impedance at the output of the charger directly affects loop characteristics. Also, an additional pole or poles may arise in the loop response because of the roll-off of the pass device's current gain (β). This effect occurs at approximately the rated unity-gain frequency of the device, divided by the transistor's low-frequency current gain. The transconductance terms for the voltage- and current-limit amplifiers ($1/1300$ and $1/300$, respectively) start to roll off at approximately 500 kHz. As a rule of thumb, it's wise to kill the loop gain at a frequency well below the point where any of these not-so-predictable poles enter the picture.

If you prefer not to go through a Bode-plot analysis of the loops to choose a compensation-capacitor value, and if you recognize that battery chargers require no optimum dynamic response, you can ensure loop stability by simply oversizing the value of the capacitor at the compensation pin. In some cases, you might have to add a resistor in series with the compensation capacitor to insert a zero in the response.

Typical values for the compensation capacitor range from 1000 pF to 0.22 μF, depending on the pass device and its configuration. With composite common-emitter configurations (for example, **Fig 11c**'s), compensation values closer to the 0.22-μF value are required to roll off the large open-loop gain that results from the β^2 term in the gain expression. Series resistance should be

TABLE 1—PERFORMANCE OF CHARGER IN FIG 12

INPUT-SUPPLY VOLTAGE	9.0 TO 13V
OPERATING-TEMPERATURE RANGE	0 TO 70°C
START-UP TRICKLE CURRENT (I_T)	10 mA (V_{IN} = 10V)
START-UP VOLTAGE (V_T)	5.1V
BULK-CHARGE RATE (I_{MAX})	500 mA (C/5)
BULK-TO-OC TRANSITION VOLTAGE (V_{12})	7.125V
OC VOLTAGE (V_{OC})	7.5V
OC-TERMINATE CURRENT (I_{OCT})	50 mA (C/50)
FLOAT VOLTAGE (V_F)	7.0V
FLOAT-TO-BULK TRANSITION (V_{31})	6.3V
VOLTAGE-LEVEL TEMPERATURE COEFFICIENT	−12 mV/°C
REVERSE CURRENT INTO CHARGER (V_{IN} = 0V)	≤5 μA

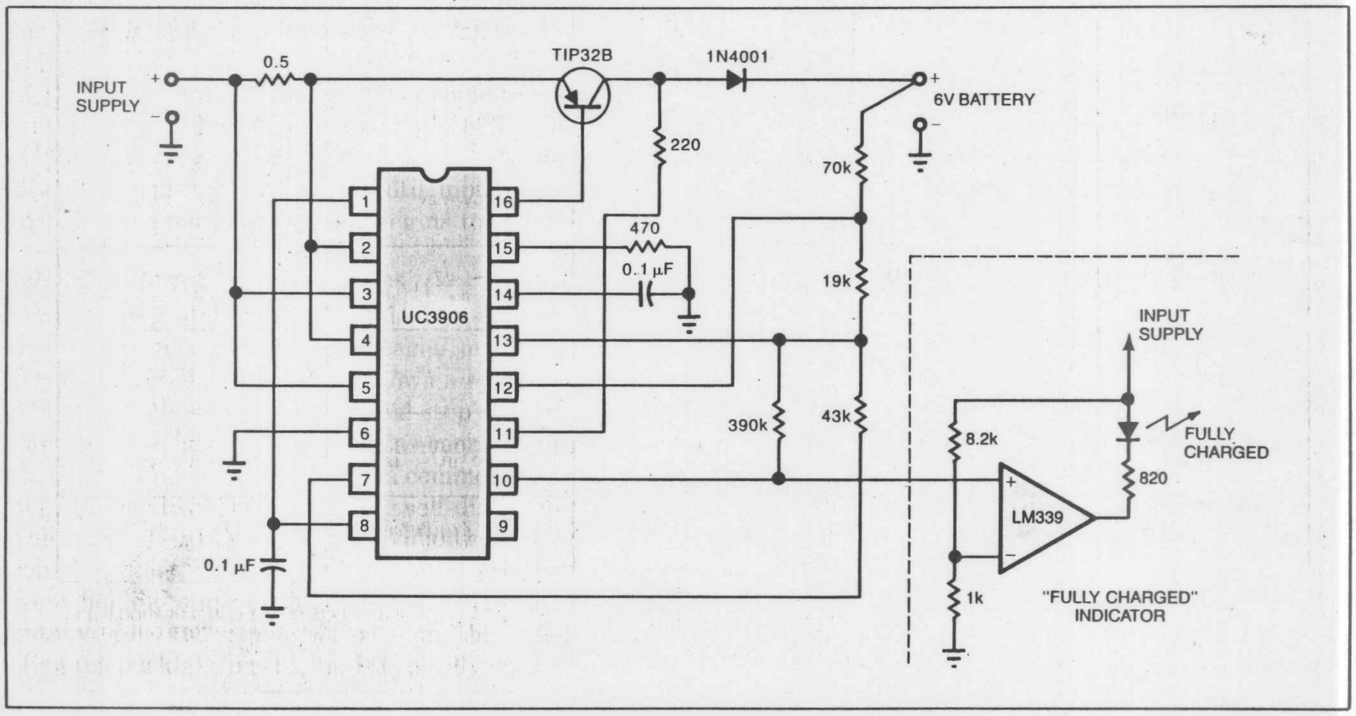


Fig 12—This dual-level float charger charges a 6V (three 2V cells), 2.5-Ahr battery. The separate "fully charged" indicator lets you see when the charge is completed. Table 1 provides the specs for the charger circuit.

You can fine-tune the charger to account for die dissipation by adjusting charger parameters at critical points in the charging cycle.

lower than 1 kΩ; it can range as low as 100Ω and still be effective.

The power dissipated by the UC3906 requires close attention because the relatively high thermal resistance (100°C/W) of the IC's DIP can result in significant differences in temperature between the IC die and the surrounding air (and battery) temperature. Different driver and pass-element configurations result in varying amounts of dissipation in the UC3906. You can reduce the dissipation by adding dropping resistors in series with the UC3906's driver **(Fig 11).** These resistors then share the power with the IC die.

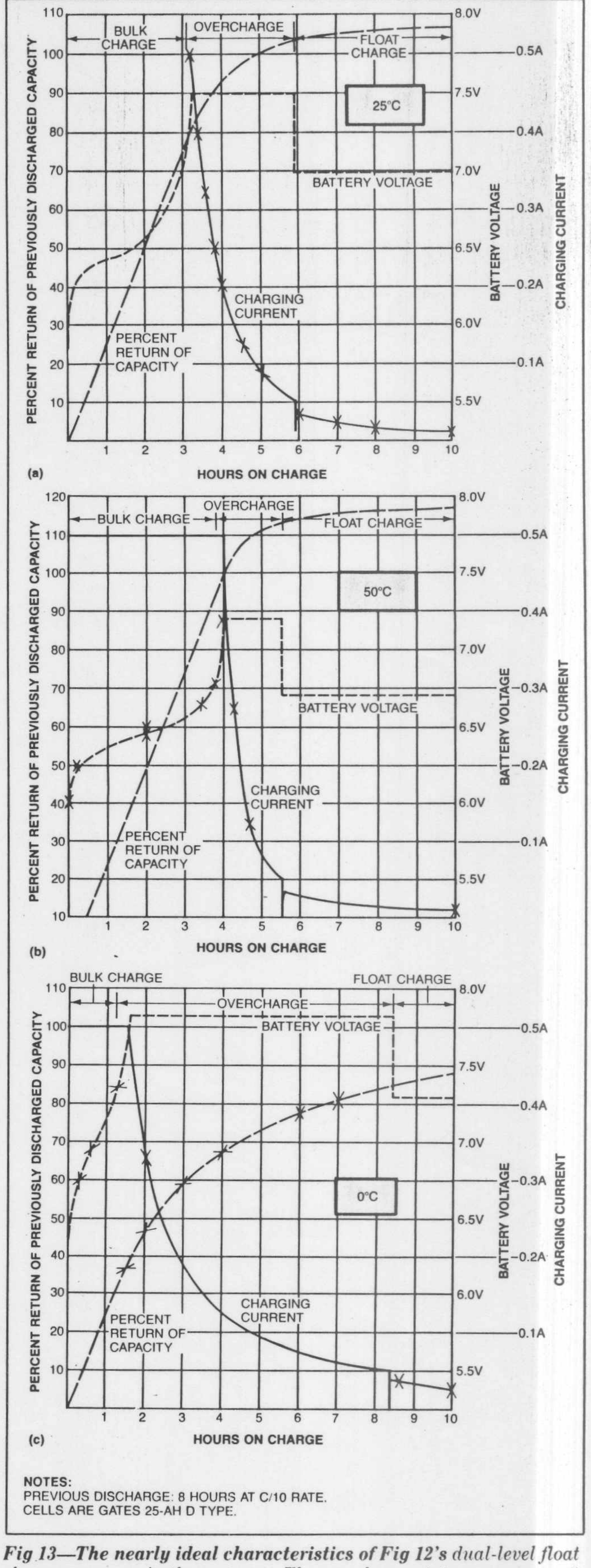
The charger parameters most affected by increased driver dissipation are the transition thresholds (V_{12} and V_{21} in **Fig 9**) because the charger supplies its maximum current at these points. Because the input offset voltages of the current amplifier and sense comparators have little temperature dependence, dissipation has no effect on current levels. Also, the charger's standby float level still tracks ambient temperature accurately because little current is required from the charger during charging.

To estimate the effects of power dissipation on the charger's voltage levels, you must calculate the power dissipated by the die at any given point, multiply the power value by the thermal resistance of the package, and then multiply this product by the product of the 3.9-mV/°C temperature coefficient of the UC3906's reference and the appropriate external-divider ratio. You can generally ignore the power-dissipation effects because in most cases they're negligible. If necessary, however, you can fine-tune the charger to account for die dissipation by adjusting charger parameters at critical points in the charging cycle.

Fig 12 represents a dual-level float charger for use with a 6V, 2.5-Ahr, sealed lead-acid battery. The specifications for this charger (at 25°C) are listed in **Table 1.** To achieve the low (1.5V) input/output differential, the charger uses a pnp pass device that can operate in the saturation region under low-input-supply conditions.

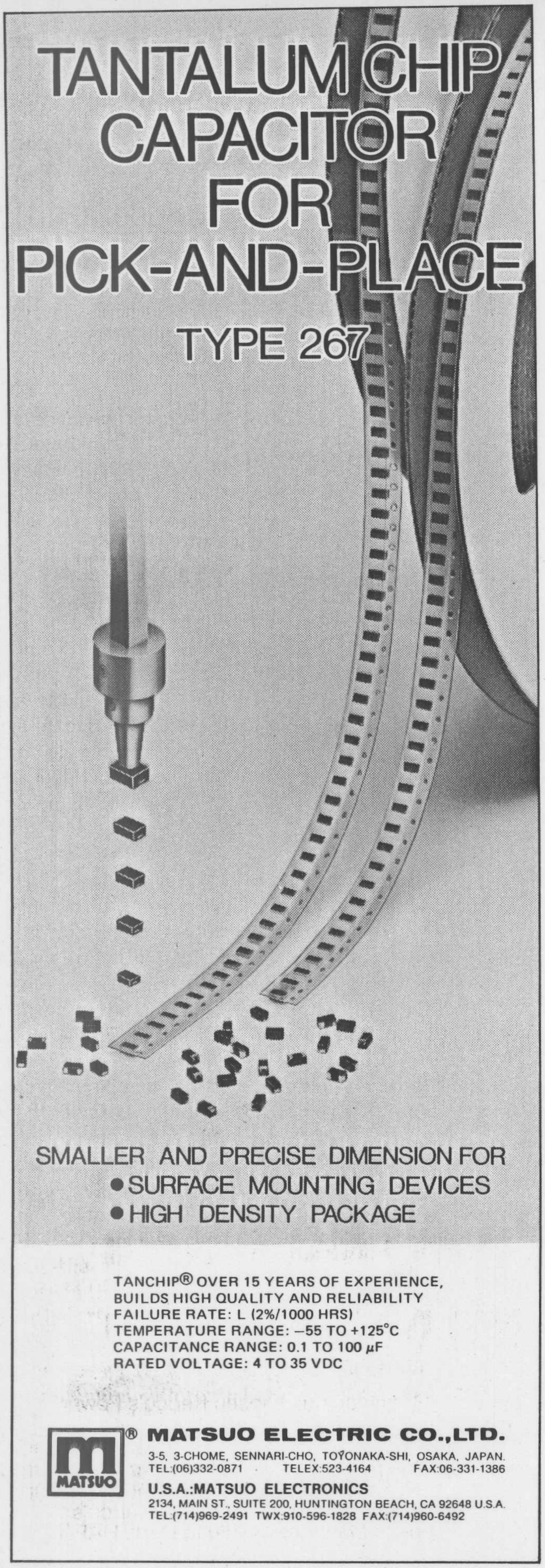
The series diode shown in **Fig 12,** necessary to satisfy the reverse-current specification, accounts for 1V of the 1.5V minimum differential. Keeping the reverse current below 5 μA also requires disconnecting the divider string when you remove input power. You accomplish the disconnection by using the input power-indicate pin as a reference for the divider string.

The driver in the UC3906 shunts the drive current from the pass device to ground. The 470Ω resistor



NOTES:
PREVIOUS DISCHARGE: 8 HOURS AT C/10 RATE.
CELLS ARE GATES 25-AH D TYPE.

Fig 13—The nearly ideal characteristics of Fig 12's *dual-level float charger are seen in these curves. The overcharge state commences at approximately 80% return of capacity, and float charging begins at a point just over 100% return. The curves represent performance at 25°C* ***(a)****, 50°C* ***(b)****, and 0°C* ***(c)****.*



CIRCLE NO 100

added between pin 15 and ground keeps the die's dissipation to less than 100 mW under worst-case conditions, assuming a minimum forward current gain of 35 at 500 mA in the pass element.

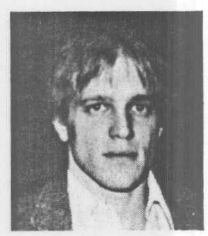
LED indicates that battery is charged

The charger in **Fig 12** includes a simple circuit to detect when the battery is fully charged; by driving an LED, the circuit lets you know when the charging process is completed. This circuit turns on the LED when the battery enters the float state. The circuit detects the entry into the float state by sensing when the state-level output turns off.

Fig 13 plots charge cycles at three temperatures: 25°C (**Fig 13a**), 50°C (**Fig 13b**), and 0°C (**Fig 13c**). The plots show battery voltage, charge rate, and percent return of previously discharged capacity. This last parameter is the integral of the charge current over the time of the charge cycle, divided by the total charge volume removed since the last full charge.

For all the curves, the previous discharge was 80% (2 Ahr) at a C/10 (250-mA) rate. The discharges were preceded by an overnight charge at 25°C. The less-than-100% return of capacity in the charge cycle at 0°C is the result of the battery's reduced capacity at this temperature. The tapering of the charge current in the overcharge state still indicates that the cells are being returned to a full state of charge. **EDN**

Author's biography



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